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On the Abundances of Heavy Elements in the Atmosphere of Procyon

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Abstract—By comparing an atlas of the spectrum of Procyon with the synthetic spectrum computed for the entire wavelength range covered by the observations (λλ3140–7470 Å), we have identified absorption lines of germanium, molybdenum, mercury, cadmium, tellurium, holmium, hafnium, rhenium, osmium, and iridium. The synthetic-spectrum method is used to determine the abundances of these elements in the atmosphere of Procyon. The derived values are close to the solar abundances of the corresponding elements (or to the meteoritic abundance for rhenium). Tellurium, which is enhanced by 0.5–0.8 dex relative to its meteoritic abundance, constitutes an exception. We analyze the set of oscillator strengths of Corliss and Bozman (1962) and show that they contain systematic errors that depend on the degree of filling of the electron shell. A summary table of the abundances of 34 *r*- and *s*-process elements in the atmosphere of Procyon is given. The abundances of all elements, except for selenium and tellurium, are close to their Solar-system values. Anomalies in the selenium abundance require confirmation.

INTRODUCTION

Procyon (α CMi), one of the brightest and closest F stars, is a well-studied object. This star is an optical binary (Procyon B is a white dwarf); its parallax and apparent angular diameter have been measured with high accuracy. Procyon has been studied by virtually all methods presently in wide use in modern astrophysics.

A detailed abundance analysis of chemical elements in the atmosphere of Procyon is necessary both for a better understanding of the evolutionary status of this star and for its use as a standard star in studies of fainter objects.

Testing the theories of formation of heavy elements (with atomic numbers 29 or greater) in the *r*-, *s*-, and *p*-processes is one of the most topical of astrophysical problems to date. For this test, data on the abundances of as many of these elements as possible in objects of different types, including solar-type stars (which α CMi is), are needed. Edmonds (1964) was the first to use the model-atmosphere method to study α CMi. Griffin (1971) and Zenina *et al.* (1976) determined the chemical composition of Procyon by the curve-of-growth method. Subsequently, the atmospheric chemical composition of Procyon was analyzed by the model-atmosphere and synthetic-spectrum methods. Leushin and Sokolov (1980) determined the abundances of 12 elements, including strontium and europium, in the atmosphere of Procyon by comparing the computed and observed line profiles in its spectrum.

In 1979, Griffin and Griffin (1979) published a high-dispersion atlas of the spectrum of Procyon covering the wavelength range 3140–7470 Å which was used in all subsequent optical studies of the chemical composition of this star. Kato and Sadakane (1982) determined the abundances of 30 elements (from Na to Os), including 16 *r*- and *s*-process elements, in the atmosphere of Procyon relative to their solar values. Steffen (1985) made a detailed spectroscopic study of the atmosphere of Procyon and derived the abundances of 28 elements, among which were 11 *r*- and *s*-process elements. Kato and Sadakane (1986) verified the enhancement of lanthanum and slight deficiency in cerium, neodymium, and samarium established by Steffen for the atmosphere of Procyon. Using the synthetic-spectrum method, these authors showed that the abundances of 13 rare-earth elements closely matched their solar values; they found that the erbium abundance deviated greatly from its solar value.

Faraggiana *et al.* (1986) identified absorption lines in the ultraviolet spectrum of Procyon (λλ2030–2371 Å) and obtained a qualitative estimate for the abundances of chemical elements in its atmosphere: the abundances of all elements studied by this author, except for Ge, Se, and Os, are close to their solar values. The osmium abundance obtained by Kato and Sadakane (1982) is close to its solar value and disagrees with the value derived by Faraggiana *et al.* (1986) from the ultraviolet spectrum. Kato (1987) found the isotopic ratio for europium in the atmosphere of Procyon to be close to solar. Orlov and Shavrina (1991) obtained the palladium abundance in the atmosphere of this star by the synthetic-spectrum method.

By 1994, the abundances of 26 *r*- and *s*-process elements in the atmosphere of Procyon had been determined. Yushchenko and Gopka (1994) identified four absorption lines of thorium in the blue part of the atlas of the spectrum of Procyon (Griffin and Griffin, 1979)

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and derived the thorium abundance in its atmosphere (it turned out to be nearly solar). Gopka and Yushchenko (1995) identified 14 absorption lines of erbium in the spectra of Procyon and the Sun and showed that the erbium abundance in the atmosphere of Procyon matches closely its solar value. Results of abundance determinations for rhenium in the atmosphere of Procyon are briefly described in Gopka *et al.* (1995) and Yushchenko and Gopka (1996).

The aim of this study is to enlarge the list of *r*- and *s*-process elements in the atmosphere of Procyon with known abundances. In our analysis, we used only elements whose abundances had not been known previously and elements for which conflicting values were given by different authors. To solve this problem, we

(1) identified the absorption lines of heavy elements that had not been identified previously in the wavelength range 3140–7470 Å by comparing the real high-dispersion spectrum of the star with the computed theoretical spectrum;

(2) determined the abundances of these elements in the atmosphere of Procyon by the synthetic-spectrum method;

(3) compared the derived abundances with their values obtained from the corresponding lines in the solar spectrum.

METHOD

We used an atlas of the spectrum of Procyon (Griffin and Griffin, 1979) covering the wavelength range 3140–7470 Å at steps of 0.005 Å as our observational data. For a more reliable line identification, we computed synthetic spectra in the above wavelength range at steps of 0.01 Å for the model atmospheres of Procyon and the Sun.

Our list of oscillator strengths of spectral lines consisted of lines from the BELLLIGHT, BELLHEAVY, and NBS files (Kurucz 1992a, 1993) and lines of iron-group elements listed in Kurucz (1991). For some of the neutral species and ions whose lines were not given in the BELLLIGHT and BELLHEAVY files (He, BI, C, OI, NaI, MgI, MgII, AlI, Si, KI, and ZnIII), we used one of the latest versions of the line list of Kurucz and Peytremann (1975). The elemental abundances used to compute synthetic spectra were taken from Anders and Grevesse (1989).

We used a modified program of Tsymbal (1991) and a number of subroutines from the SPANSAT software package (Gadun and Sheminova, 1988) to compute the synthetic spectrum.

We took the parameters of the atmosphere of Procyon from Steffen (1985): $T_{\text{eff}} = 6750$ K, $\log g = 4.04$, $v_{\text{turb}} = 2.1$ km s^{-1}, and [A/H] = 0.0; Kurucz's (1979) grid of model atmospheres was employed for the computations.

To fit the observed spectrum of Procyon, we convolved the synthetic spectrum with a Gaussian instrumental profile with FWHM corresponding to the spectral resolution of our observational data ($\lambda/\Delta\lambda \sim 150000$) and macroturbulent velocity of 3.5 km s^{-1}. A Gaussian macroturbulence model was employed (Gray, 1976). Our adopted macroturbulent velocity is slightly greater than the value of 2.0 km s^{-1} obtained by Leushin and Sokolov (1980). We thus implicitly allowed for the rotational velocity. Kato and Sadakane (1986) used macroturbulence (5 km s^{-1}) as a mechanism for line broadening in the synthetic spectrum. Gray (1981) determined the macroturbulent velocity in the atmosphere of Procyon using a radial–tangential model. This author obtained the values of 7 and 2.8 km s^{-1} for the macroturbulence and the rotational velocity, respectively. Atroshchenko *et al.* (1989) found the rotational velocity of Procyon to lie within the range 2 to 6 km s^{-1}.

We smoothed the observed spectrum with a Gaussian with FWHM of 0.01–0.02 Å and replaced unknown lines with faked iron lines. Analysis of possible errors is given in our previous paper (Yushchenko and Gopka 1994).

In order to eliminate uncertainties arising from possible errors in the oscillator strengths, we referenced the derived abundances to the values obtained from the corresponding lines in the solar spectrum. The solar flux atlas of Kurucz *et al.* (1984) was our source of observational data. We determined the equivalent widths of absorption lines in the solar spectrum by fitting the line profile with a Gaussian. For some of the lines, we used the method and programs of Cassatella (1976) to separate the blends. We determined the solar abundances by the model-atmosphere method using the WIDTH-9 program of Kurucz. It is well known that using different solar model atmospheres results in an abundance difference as great as 0.2 dex (Gurtovenko and Kostyk, 1989). We used the solar model atmosphere from the same grid as that of Procyon to reduce the effect of uncertainties arising from differences in the model atmospheres (Kurucz 1979). The microturbulent velocity for the solar atmosphere was taken to be 0.9 km s^{-1} (Gopka and Yushchenko, 1994).

Steffen (1985) showed that the equivalent widths of weak lines derived from the atlas of the spectrum of Procyon were underestimated by approximately 10%. In order to take this systematic error into account, our abundances in the atmosphere of Procyon should be increased by 0.05 dex (Kato and Sadakane, 1986).

When we completed this study, we gained access to a new grid of stellar model atmospheres (Kurucz, 1992b). When Kurucz's new models are used, the abundances of the chemical elements in the atmosphere of Procyon relative to their solar values increase by approximately 0.1 dex. Below, we give a summary table of the abundances of *r*- and *s*-process elements in the atmosphere of Procyon as of 1995 (Table 2). The values given in this table were all obtained on the basis of Kurucz's (1979) grid of stellar model

N	Code	λ, Å 3170+	%	*R*	log*gf*	Δ*gf*
13	260	2.506	99	72	−2.37	
14	260	2.587	91	90	−2.92	
15	681	2.615	2	93	−0.84	−0.69
16	260	2.652	70	90	−2.97	
17	261	2.664	1	90	−3.81	0.00
18	251	2.684	35	92	−2.79	0.58
19	441	2.688	1	93	.00	0.01
20	121	2.708	75	94	−2.00	0.93
21	250	2.711	3	94	−1.12	0.00
22	240	2.715	2	94	−1.56	0.00
23	220	2.732	5	93	−2.06	0.00
24	421	2.758	67	91	−0.83	0.13
25	691	2.825	82	88	−0.26	0.27
26	260	2.899	65	85	−2.78	
27	221	2.908	1	83	−4.30	0.00
28	251	2.940	91	76	−1.32	.20
29	260	2.970	35	82	−2.89	
(*S*/*N*) = 84						

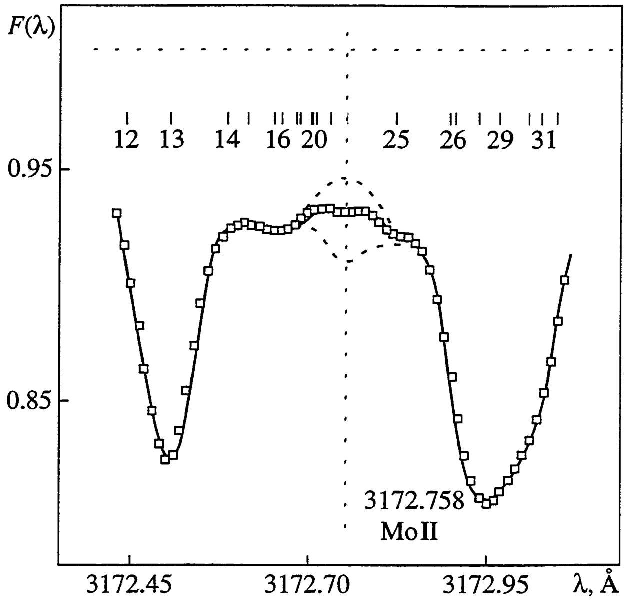

Fig. 1. Comparison of the observed spectrum of Procyon (solid line) near the MoII λ3172.758 Å line with the synthetic spectra (dashed lines) computed for the molybdenum abundance that is 0.2 dex larger and smaller than the best-fit value (squares). The table is described in the text.

N	Code	λ, Å 3220+	%	*R*	log*gf*	Δ*gf*
13	260	0.511	68	78	−2.64	
14	221	0.555	89	62	−1.99	−1.80
15	270	0.621	92	84	−1.45	1.13
16	721	0.654	15	90	0.14	−0.34
17	250	0.655	20	90	−1.32	−0.30
18	260	0.686	64	90	−3.05	
19	260	0.729	94	82	−2.63	
20	770	0.776	48	84	−0.51	0.10
21	250	0.796	9	86	−1.56	−0.13
22	261	0.835	98	71	−3.19	0.01
23	581	0.868	5	89	−0.25	−0.33
24	260	0.908	83	90	−2.94	
26	220	0.934	5	92	−1.47	0.16
25	261	0.931	11	92	−2.00	0.33
27	260	0.968	88	88	−2.82	
(*S*/*N*) = 149						

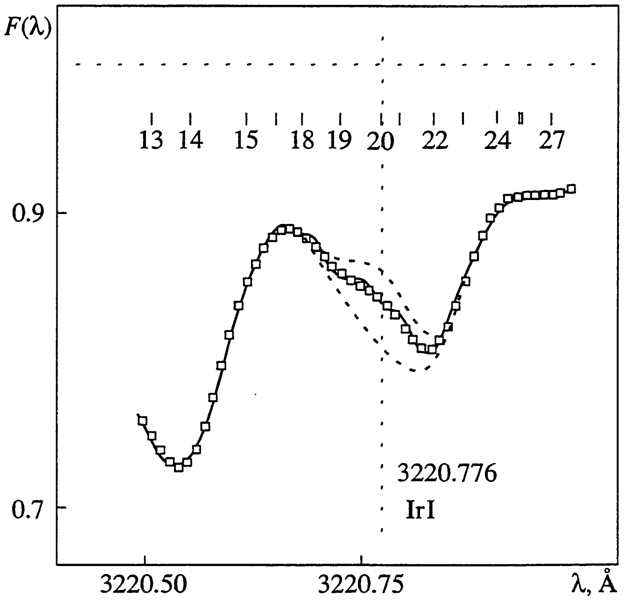

Fig. 2. Same as in Fig. 1 but for the IrI λ3220.776 Å line.

atmospheres. Only the study of Leushin and Sokolov (1980) constitutes an exception. To preserve a greater degree of homogeneity of Table 2, we used the old grid of stellar model atmospheres (Kurucz, 1979).

RESULTS

By comparing the observed and synthetic spectra of Procyon, we identified nine absorption lines belonging to eight *r*- and *s*-process elements: Ge, Mo, Ag, Cd, Ho, Hf, Os, and Ir. The abundances of these elements (except for Ge and Os) in the atmosphere of Procyon have not been analyzed using optical absorption lines either by the model-atmosphere method or by the synthetic-spectrum method. We determined the abundances of germanium and osmium in order to confirm the anomalous abundances of these elements (see above) found by Faraggiana *et al.* (1986).

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Table 1. Abundances of some heavy elements in the atmosphere of Procyon A

Z	Element	λ, Å	loggf	logN_*	W_*, mÅ	$W_\odot$, mÅ	log$N_\odot$	Δlog$N$	λ_M	Id$_M$	W_M, mÅ
32	GeI	3269.489	–0.92	3.21	15	46	3.31	–0.10	9.504	GeI	44
42	MoII	3172.758	–0.83	2.10	4	–	–	(+0.18)	–		
47	AgI	3280.679	–0.05	1.14	13	43	1.17	–0.03	0.671	AgI	44
48	CdI	3261.050	–2.47	2.03	3	22	2.03	0.00	1.065	CdI	23
52	TeI	3175.147	–0.03*	3.04	10	–	–	(+0.80)	–		
67	HoII	4152.585	–0.89	0.46	2	–	–	(+0.20)	–		
72	HfII	3176.855	–0.63	1.20	9	7	0.95	+0.25	6.835	HfII	7
72	HfII	3399.793	–0.49	0.72	13	41	–	(–0.16)	9.808	NH	38
75	ReII	3303.207	0.69*	0.40	4	–	–	(+0.13)	–		
76	OsII	3173.931	0.74*	0.13	6	5	0.14	–0.01	3.950	unidentified	5
77	IrI	3220.776	–0.51	1.50	7	19	1.47	+0.03	0.775	IrI	32

The results of fitting the observed spectrum of Procyon near the Mo and Ir lines with a synthetic spectrum are presented in Figs. 1 and 2. In each figure, the position of the line in question is marked by the dotted vertical line. The wavelength of the line under study, symbol of the element, and its degree of ionization are also shown in these figures. The synthetic spectra computed for the abundances of the element under consideration differing by 0.2 dex from the best-fit value are indicated by the dashed lines. The vertical bars at the top of Figs. 1 and 2 show the positions of the lines used to compute the synthetic spectra and line numbers.

The first two columns of the tables in the left parts of the figures give line numbers in the figure and codes of the chemical elements. Code 260 is assigned to neutral iron. The next three columns give the last digits of the wavelengths; the line contribution to the absorption coefficient at a given wavelength (%); and the residual intensity of the line in the synthetic spectrum that was not convolved with the macroturbulent velocity and instrumental profile (R), assuming that the continuum level is 100. The next-to-last column of the tables gives the logarithms of the oscillator strength of a give line (loggf) according to our line list. The last column lists the corrections (Δgf) to the logarithms of the oscillator strengths that are needed to reproduce the observed spectrum. No corrections to the oscillator strengths are given for the unknown lines which we fitted by lines of neutral iron with energies below 3 eV.

As was noted above, we smoothed the observed spectrum of Procyon with a Gaussian. The rms deviation of the smoothed spectrum from the unsmoothed spectrum was calculated from the formula $S/N = 1.0/\left(\sum_{i=1}^{n}(x_i - y_i)^2/(n-1)\right)^{1/2}$, where x and y denote, respectively, the unsmoothed and smoothed spectra, and is given under the table. As can be seen from Figs. 1 and 2, this rms deviation is close to 100, implying a rather low noise level in the atlas of Procyon.

The results of our analysis are summarized in Table 1. The first four columns give, respectively, atomic number Z of the element, its symbol and degree of ionization, line wavelength, and logarithm of the oscillator strength (loggf). We took the oscillator strengths from the BELLHEAVY file. The values of loggf obtained by Corliss and Bozman (1962) are marked by an asterisk. Column 5 gives the abundances of the elements in the atmosphere of Procyon determined by the synthetic-spectrum method (log N_*). The equivalent widths (W_*) of the absorption lines corresponding to the abundances obtained by the synthetic-spectrum method are listed in column 6.

Column 7 of the table give the equivalent widths $W_\odot$ that we determined for the corresponding absorption lines from the solar-disk spectrum of Kurucz *et al.* (1984). The solar abundances log $N_\odot$ derived from the above equivalent widths are given in column 8.

Column 9 gives the abundance differences Δlog$N$ for the elements in the atmospheres of Procyon and the Sun. The values without parentheses are the differences of the values given in columns 5 and 8. The values in parentheses are the differences of the abundances in the atmosphere of Procyon given in column 5 and the corresponding solar abundances obtained by Grevesse and Noels (1993). The data of Moore *et al.* (1966) are presented in the last three columns of the table for comparison: the last digits of the wavelengths of spectral lines λ_M, their identifications Id$_M$, and equivalent widths W_M, respectively.

Results of Gopka *et al.* (1995) and Yushchenko and Gopka (1996), who determined the abundances of tellurium and rhenium in the atmosphere of Procyon by a similar method, are also presented in Table 1. The solar abundances of these elements are not known (Grevesse and Noels, 1993). Since there are no lines in the solar spectrum at the positions of the tellurium and rhenium lines under study, column 9 in Table 1 gives the differences between the abundances of these elements in the

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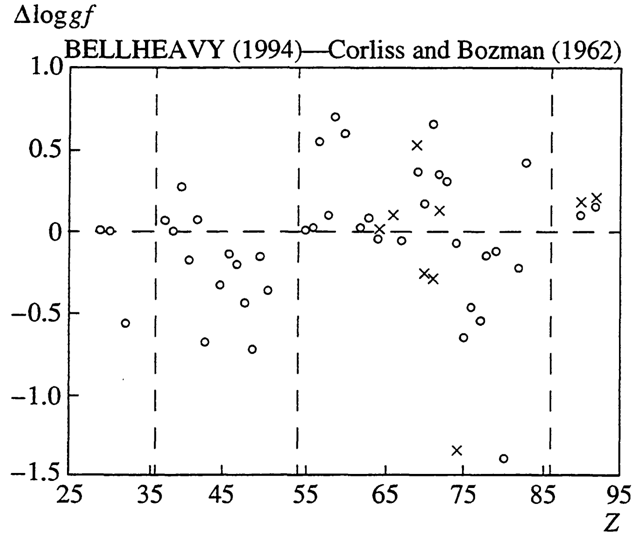

Fig. 3. Mean differences between the oscillator strengths of spectral lines contained both in the BELLHEAVY file and in the list of Kurucz and Peytremann (1975) for the chemical elements with the atomic numbers from 29 to 92. The atomic numbers are along the x axis, and the mean differences are along the y axis. The horizontal dashed line corresponds to zero difference. The vertical dashed lines are for the noble gases krypton, xenon, and radon ($Z = 36, 54, 86$). The mean differences between the oscillator strengths for neutral species and ions are indicated by the circles and crosses, respectively.

atmosphere of Procyon that we found and their meteoritic values (Grevesse and Noels, 1993).

THE SCALE OF OSCILLATOR STRENGTHS OF CORLISS AND BOZMAN (1962)

For the absorption lines of tellurium, rhenium, and osmium (see Table 1), we used the oscillator strengths determined by Corliss and Bozman (1962). The list of oscillator strengths for lines of the elements with atomic numbers $Z \geq 29$ compiled by Kurucz and Peytremann (1975) included only the oscillator strengths of Corliss and Bozman (1962). No other sources of oscillator strengths were used by Kurucz and Peytremann for the heavy elements. Since the list of Kurucz and Peytremann (1975) is fairly complete and readily available on magnetic media, this list and its later versions available on magnetic tapes had been widely used in numerous abundance analyses of stellar atmospheres over almost twenty years. Only a few years ago, Kurucz, Bell, and Warner compiled a new list of oscillator strengths for heavy elements—the BELLHEAVY file (Kurucz, 1992a, 1993). The latest version of the BELLHEAVY file (1994) contains data for 38453 spectral lines for which the oscillator strengths were taken from 80 sources. The oscillator strengths for 6062 lines (16% of the total number of lines in the BELLHEAVY file) were determined by Corliss and Bozman (1962).

It is evident from the above discussion that the study of Corliss and Bozman (1962) is currently one of the most complete sources of oscillator strengths for absorption lines of heavy elements, and it will be used for some time in astrophysics.

Since many of the oscillator strengths of spectral lines of heavy elements were redetermined in later studies and collected in the BELLHEAVY file, it became possible to assess the quality of the set of oscillator strengths of Corliss and Bozman which has been used for more than three decades.

We computed the mean differences between the oscillator strengths of spectral lines contained both in the BELLHEAVY file and in the list of Kurucz and Peytremann (1975) for the elements with the atomic numbers from 29 to 92. The results of our computations are presented in Fig. 3, in which the mean differences between the oscillator strengths of the lines of a given element according to the more recent data collected in the BELLHEAVY file (the 1994 version) and the corresponding values from the list of Corliss and Bozman (1962) are plotted versus atomic numbers of the elements. The horizontal dashed line corresponds to zero difference. The noble gases krypton, xenon, and radon ($Z = 36, 54, 86$) are indicated by the vertical dashed lines. The mean differences between the oscillator strengths for neutral species and ions are shown by the circles and crosses, respectively.

It is evident from Fig. 3 that the mean differences between the oscillator strengths for the elements of the fifth and sixth periods of the periodic table of the elements show similar patterns. The mean differences near the beginning of the period are close to zero or positive; as the electron shells are filled, negative mean differences begin to dominate. Unfortunately, the elements near the end of the periods are poorly represented. Their only representative, bismuth ($Z = 83$), suggests that both positive and negative differences are possible for the oscillator strengths of lines of the elements immediately preceding the noble gases. The mean that differences between the oscillator strengths for the elements of the fourth and sevenths periods fit in with the described picture.

ANALYSIS OF RESULTS

It can be seen from Table 1 that nearly solar abundances of the corresponding elements can be obtained by using the oscillator strengths from the BELLHEAVY file, except for the tellurium and osmium oscillator strengths of Corliss and Bozman (1962) contained in this file. A direct differential abundance analysis of these elements in the atmospheres of Procyon and the Sun reveals no significant errors in the oscillator strengths gathered in the BELLHEAVY file.

For the elements for which the oscillator strengths of their lines were taken from the list of Corliss and

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Bozman (1962), the situation is different. Let us consider each of these elements separately.

Tellurium

The Te abundance in the solar atmosphere is not known (Grevesse and Noels, 1993). Although there is no line at the position of the Te λ3175.147 Å line under consideration in the observed spectrum of the Sun, our analysis by the synthetic-spectrum method suggests that the solar abundance of tellurium is close to its meteoritic value $\log N(\mathrm{Te})_{\mathrm{met}} = 2.25$ (Grevesse and Noels, 1993). We used the oscillator strength of the Te line given by Corliss and Bozman (1962) to estimate the abundance of tellurium in the solar atmosphere from a portion of the spectrum containing this line: $\log N(\mathrm{Te})_{\odot} = 1.93$. It follows from the assumption of a nearly meteoritic abundance of tellurium in the solar atmosphere that there is no gross error in the oscillator strength of the Te line in question, and that the tellurium abundance in the atmosphere of Procyon derived from the λ3175.147 Å line is enhanced by 0.8 dex relative to its meteoritic value.

Rhenium

The Re abundance in the solar atmosphere is also unknown. There is no line at the position of the Re λ3303.207 Å line in the observed spectrum of the Sun. We estimated the rhenium abundance in the solar atmosphere by the synthetic-spectrum method to be $\log N(\mathrm{Re})_{\odot} = 0.02$, in close agreement, within the limits of error, with its meteoritic value $\log N(\mathrm{Re})_{\mathrm{met}} = 0.27$ (Grevesse and Noels, 1993). The Re abundance in the atmosphere of Procyon that we obtained matches, within the limits of error, its meteoritic value.

Osmium

The Os abundance in the atmosphere of Procyon (column 5 of Table 1) is 1.37 dex lower than its solar value. There is a distinct line at the position of the Os line in the solar-disk spectrum (Kurucz *et al.*, 1984) and in the synthetic spectrum that we computed for the Sun, allowing us to determine the osmium abundance in the solar atmosphere from the Os λ3173.931 Å line (column 5 of Table 1). The difference between the Os abundances in the atmospheres of Procyon and the Sun is 0.01 dex, suggesting that the oscillator strength that we used for this line was overestimated by one and a half orders of magnitude.

Thus, of the three oscillator strengths of Corliss and Bozman (1962) that we used in our analysis, two values of $\log gf$ (for the Te and Re lines) contain no gross errors and one value was overestimated by one and a half orders of magnitude (for the Os line). This is in agreement with the systematic errors in the scale of oscillator strengths of Corliss and Bozman (1962) that we considered above. For osmium (Fig. 3), we could expect the oscillator strengths of its lines to be consistent with the later determinations or be overestimated.

It should also be mentioned that for the HfII λ3399.793 Å line, column 9 in Table 1 gives the difference between the hafnium abundance in the atmosphere of Procyon that we derived from this line and its solar value obtained by Grevesse and Noels (1993). The reason is that the NH molecule gives the largest contribution to the corresponding line. In the spectrum of Procyon, the molecular line disappears. We take $\Delta \lg A(\mathrm{Hf}) = 0.11$ computed as the weighted mean of the two values given in column 9 of Table 1 to be the final hafnium abundance in the atmosphere of Procyon relative to its solar value. We assigned the weights 2 and 1 to the values obtained from the λ3176.855 and λ3399.793 Å lines, respectively.

HEAVY-ELEMENT ABUNDANCES IN THE ATMOSPHERE OF PROCYON A

A review of the determinations of heavy-element abundances in the atmosphere of Procyon by the model-atmosphere and synthetic-spectrum methods listed above led us to conclude that the abundances of virtually all heavy elements in the atmosphere of this star match, within the limits of error, their solar or meteoritic values. Germanium, selenium, osmium [according to Faraggiana *et al.* (1986), who analyzed the ultraviolet spectrum], and tellurium (the result of our study) constitute an exception.

Faraggiana *et al.* (1986) found the germanium abundance to be anomalous, $\log N(\mathrm{Ge}) = 3.0$ (0.4 dex lower than the solar value). Our determination of the Ge abundance in the photosphere of Procyon relative to its solar value (–0.1 dex) contains no errors related to the oscillator strengths and does not confirm the anomalous abundance of this element in the atmosphere of this star.

The selenium abundance derived by Faraggiana *et al.* (1986) is 2.4 dex lower than its solar value. In the periodic table of the chemical elements, selenium ($Z = 34$) is located near the end of the fourth period (krypton, $Z = 36$). As was shown above, the oscillator strengths of Corliss and Bozman (1962) for the elements located near the end of the periods of the periodic table may contain significant systematic errors. Faraggiana *et al.* (1986) took the oscillator strength ($\log gf = 0.26$) for the Se λ2074.79 Å line from the modified list of Kurucz and Peytremann (1975). If the oscillator strength of Corliss and Bozman (1962) is used for this line ($\log gf = -1.44$), the anomaly in the selenium abundance is considerably reduced. Since the BELLHEAVY file contains no Se line in the spectral range 3000 to 8000 Å, we cannot derive the selenium abundance in the atmosphere of Procyon from other lines.

The Te abundance in the atmosphere of Procyon that we found from the λ3174.147 Å line is enhanced relative to its meteoritic value by 0.8 dex. Faraggiana *et al.* (1986) detected five Te lines in the synthetic spectrum

N	Code	λ, Å 2140+	%	R	$\log gf$	Δgf
27	261	2.416	48	49	−1.40	−0.47
28	251	2.423	1	49	−3.38	0.00
29	231	2.433	9	57	−1.63	0.00
30	281	2.452	1	10	−0.78	0.00
31	260	2.477	99	3	−0.43	
32	251	2.517	1	79	−1.48	0.00
33	240	2.533	3	89	−3.23	−0.10
34	260	2.569	98	22	−2.91	−0.55
35	251	2.730	63	28	−1.91	0.60
36	231	2.747	67	19	−2.71	0.20
37	261	2.755	14	19	−3.38	−0.10
38	281	2.756	1	29	−1.81	0.00
39	71	2.773	36	51	−4.76	−0.20
40	261	2.767	29	51	−1.01	0.00
42	251	2.819	1	2	−3.13	0.00
41	520	2.822	99	2	−0.40	0.48
43	221	2.879	96	29	−1.73	0.02
44	261	2.992	99	0	−3.53	0.30
45	231	3.041	99	1	−0.87	0.11

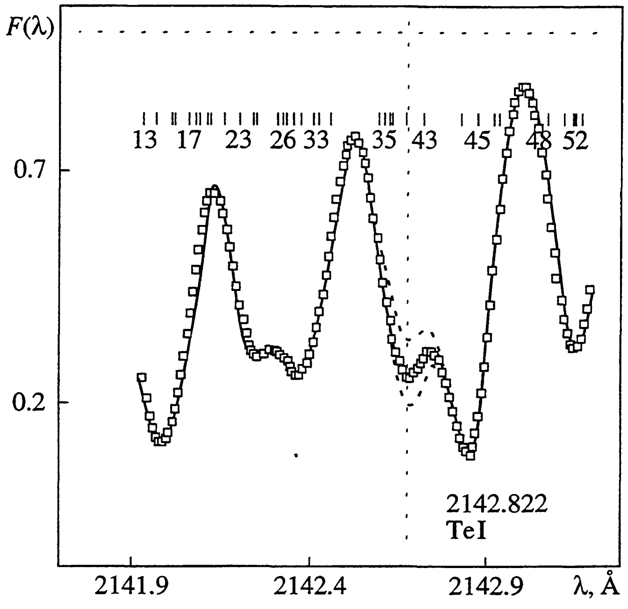

Fig. 4. Comparison of the observed IUE spectrum of Procyon (solid line) near the TeI λ2142.822 Å line with the synthetic spectra (dashed lines) computed for the meteoritic abundance of tellurium and for the abundance than is 1.0 dex greater than its meteoritic value. The best-fit synthetic spectrum is shown by the squares.

of Procyon and, having identified them in the observed spectrum, concluded that tellurium was definitely present in the atmosphere of Procyon. We computed the synthetic spectra in the vicinity of these five lines of tellurium and compared them with the two observed spectra of Procyon obtained by Faraggiana *et al.* (1986) with different spectral resolutions. These authors used the oscillator strengths from the modified list of Kurucz and Peytremann (1975) for the Te lines. In this list, the wavelengths correspond to those of Corliss and Bozman (1962), while the oscillator strengths are greater than those of Corliss and Bozman (1962) by more than one order of magnitude. The oscillator strengths from the version of the BELLHEAVY file that we used in our analysis correspond to those of Corliss and Bozman, while the wavelengths were refined, with the differences reaching 0.15 Å.

From the synthetic spectra that we computed for the five Te lines in the ultraviolet, we chose the λ2142.822 Å resonance line which was rather strong and unblended in the spectrum of Procyon: its central depth in the synthetic spectrum of Procyon convolved with the macroturbulent velocity and instrumental profile is 0.55. A comparison with the observed spectrum of Procyon indicates that the best agreement is achieved if the Te abundance in the atmosphere of Procyon is increased by 0.5 dex.

Figure 4 shows the synthetic spectrum fitted to the IUE spectrum of Procyon published by Faraggiana *et al.* (1986) in the vicinity of the Te line mentioned above. The notation in Fig. 4 is generally the same as in Figs. 1 and 2, except that the dashed lines indicate the synthetic spectra of Procyon computed for the meteoritic abundance of tellurium and for its abundance increased by 1.0 dex. Note that the oscillator strength of the Te λ2142.822 Å line was determined by Corliss and Bozman (1962).

The osmium abundance in the atmosphere of Procyon was determined by Kato and Sadakane (1982), who found it to be nearly solar, and by Faraggiana *et al.* (1986), who detected an anomaly in the abundance of this element. We found the osmium abundance in the atmosphere of Procyon to be nearly solar. Note that in contrast to the results of Faraggiana *et al.*, both our results and those of Kato and Sadakane are free of errors related to the oscillator strengths.

Thus, the abundances of most of the *r*- and *s*-process elements in the atmosphere of Procyon match, within the limits of the errors, their solar values (or the meteoritic abundance for rhenium). Tellurium shows an enhancement of 0.5–0.8 dex. The anomaly in the selenium abundance needs confirmation.

The published data on the abundances of *r*- and *s*-process elements in the atmosphere of Procyon A are summarized in Table 2. Columns 1 and 2 of Table 2 give atomic numbers of the elements, their symbols and degree of ionization, respectively. The abundance of a given element in the atmosphere of Procyon A relative to its solar value ($\Delta\log N$) is given in column 3. The values without parentheses were obtained from a differential abundance analysis of the element in question in the atmospheres of Procyon and the Sun. The values in parentheses are the differences between the absolute abundance of the element in the atmosphere of Procyon

Table 2. Abundances of *r*- and *s*-process elements in the atmosphere of Procyon A

Z	Element	Δlog*N*	σ	*n*	Reference	*Z*	Element	Δlog*N*	σ	*n*	Reference
29	CuI	−0.04	0.30	3	KS82	58	CeII	−0.08	0.09	8	St85
	I	0.01	0.09	3	St85		II	−0.03	0.17	12	KS86
30	ZnI	−0.16	0.30	3	KS82	59	PrII	−0.09		1	KS86
	I	−0.05	0.12	3	St85	60	NdII	−0.14	0.07	5	St85
32	GeI	(−0.4)		1	Fr86		II	−0.08	0.20	11	KS86
	I	−0.10		1	*	62	SmII	−0.10	0.11	4	St85
34	SeI	(−2.4)		1	Fr86		II	−0.06	0.26	8	KS82
38	SrII	(−0.1)	0.2	3	LS80	63	EuII	(0.4)	0.3	1	LS80
	I	−0.20		1	KS82		II	0.03	0.09	3	St85
	II	0.11		2	KS82		II	−0.01	0.07	5	KS86
	I	0.07		1	St85	64	GdII	0.00	0.15	5	KS86
	II	0.16	0.38	3	St85	65	TbII	−0.01		1	KS86
39	YII	0.05	0.14	8	KS82	66	DyII	−0.04	0.23	5	KS86
	II	0.06	0.11	9	St85	67	HoII	(0.20)		1	*
40	ZrII	0.02	0.08	5	KS82	68	ErII	−0.19	0.15	2	KS86
	II	0.03	0.08	5	St85		II	−0.04	0.04	14	GY95
41	NbI	0.13		1	KS82	69	TmII	0.02	0.51	4	KS86
42	MoII	0.12		1	*	70	YbII	−0.04		1	KS86
44	RuI	0.04	0.30	2	KS82	71	LuII	−0.01		1	KS86
46	PdI	−0.16		1	KS82	72	HfII	0.11	0.15	2	*
	I	(−0.1)		1	OS91	75	ReII	(0.13)		1	YG96
47	AgI	−0.03		1	*	76	OsII	−0.09		1	KS82
48	GdI	0.00		1	*		II	(−1.3)		1	Fr86
52	TeI	(0.67)	0.14	2	GD95,*		II	−0.01		1	*
56	BaII	0.23	0.30	5	KS82	77	IrI	+0.03		1	*
	II	0.13	0.10	4	St85	90	ThII	(0.07)	0.16	4	GD95
57	LaII	0.22	0.09	3	St85						
	II	−0.05	0.15	10	KS86						

The following abbreviations are used: LS80 for Leushin and Sokolov (1980), KS82 for Kato and Sadakane (1982), St85 for Steffen (1985), KS86 for Kato and Sadakane (1986), Fr86 for Faraggiana *et al.* (1986), OS91 for Orlov and Shavrina (1991), GD95 for Gopka *et al.* (1995), GY95 for Gopka and Yushchenko (1995), YG96 for Yushchenko and Gopka (1996), * for this paper.

A and its mean solar abundance according to Grevesse and Noels (1993). We used the thorium abundance in the solar atmosphere derived by Anders and Grevesse (1989). For tellurium and rhenium, we give the abundance differences relative to their meteoritic values (Grevesse and Noels, 1993).

Errors in the abundances (σ) taken from the corresponding papers are given in column 4 of Table 2. Column 5 gives the number of lines used in a given determination.

The references are listed in column 6.

We did not use the abundances of rare earths in the atmosphere of Procyon obtained by Kato and Sadakane (1982) to compile Table 2 because these abundances were redetermined by the same authors in a later study (Kato and Sadakane, 1986). For tellurium, we give the mean of the value of Gopka *et al.* (1995) and the Te abundance derived in this study from the λ2142.822 Å line.

DISCUSSION

Steffen (1985) emphasized that one of the aims of his study was to search for an enrichment of the atmosphere of the primary component of the binary system Procyon, Procyon A, in heavy elements as a result of mass loss from its companion, presently the white dwarf Procyon B; Procyon B must have lost a significant fraction of its mass over the course of its evolution, possibly in explosion processes.

We established that the atmosphere of Procyon A is enriched in tellurium. According to Cameron (1982), the two most abundant tellurium isotopes in the Solar system (^{128}Te and ^{130}Te), whose contribution to the total tellurium abundance is 66%, are produced exclusively by the *r*-process. The ^{125}Te and ^{126}Te isotopes, whose contribution is 25%, are formed in both the *r*- and *s*-processes. Thus, more than two-thirds of the tellurium atoms in the Solar system are produced in the *r*-process.

The abundance curve for nuclides in the Solar system shows double peaks near the mass numbers A = 125–145 and A = 190–210. The reason for the splitting of the peaks is that each peak is shaped either by the *r*-process or by the *s*-process. The ^{128}Te and ^{130}Te isotopes lie exactly at the peak of the abundance curve for the heavy nuclides formed in the *r*-process (Cameron 1982).

Unfortunately, we do not know the isotopic composition of tellurium in the binary system Procyon. Does it match the isotopic composition of tellurium in the Solar system? Kato (1987) found the isotopic composition of europium in the atmosphere of Procyon A to be nearly solar. Taking this result into account, we may suggest that the isotopic composition of tellurium in this star also matches its solar composition. Thus, the atmosphere of Procyon A is enriched in an element that may have formed in the *r*-process. At the same time, the abundance of another *r*-process element, thorium, does not differ markedly from its solar value.

Using new, more accurate oscillator strengths for Te absorption lines may produce quite different results. However, we cannot assert beforehand that the chemical composition of Procyon A, a component of a binary, must be identical to that of the Sun.

Recall that using Kurucz's (1992b) new grid of stellar model atmospheres to perform a differential analysis of the abundances of elements in the atmosphere of Procyon relative to their solar values gives values that are 0.1 dex higher. If we add 0.1 dex to all the abundances listed in Table 2, there will be virtually no negative values in this table. Thus, a slight enhancement of heavy elements in the atmosphere of Procyon A is possible. To test this assumption, a detailed abundance analysis of all elements in the atmosphere of Procyon, including the study of a model atmosphere of this star, is needed.

New observational data obtained with high signal-to-noise ratio both in the visible and in the ultraviolet will make it possible to refine the abundances of elements in the atmosphere of Procyon and enlarge the list of these elements.

CONCLUSIONS

1. We found the abundances of germanium, molybdenum, silver, cadmium, holmium, hafnium, rhenium, osmium, and iridium in the atmosphere of Procyon A to be close to their Solar-system values.

2. Tellurium is enhanced in the atmosphere of this star by 0.5–0.8 dex relative to its meteoritic abundance.

3. We give a summary table for the abundances of 34 *r*- and *s*-process elements in the atmosphere of Procyon A. We show that the abundances of all elements, except for selenium and tellurium, are close to their values in the Solar system. The anomaly in the Se abundance needs confirmation.

4. By comparing the high-dispersion atlases of the spectra of the Sun and Procyon with their synthetic spectra, we identified the previously unidentified Os λ3173.931 Å line.

High signal-to-noise ratio spectroscopy both in the ultraviolet and in the optical and more accurate oscillator strengths of spectral lines are needed to study the chemical composition of Procyon in more detail.

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